Remote Sensing of Nearshore Water Quality Using Bio-Optical Modeling and Retrieval Techniques

Sima Bagheri, New Jersey Institute of Technology
Arnold Dekker, Vrije Universiteit

1. Study Area

The study area is the Hudson/Raritan Estuary and the New Jersey nearshore waters (figure 1). The estuary is a typical partially mixed drowned river estuary (Oey et al., 1985) and is relatively shallow (< 8 m). The net movement of water within the estuary is counter-clockwise. The estimated flushing time of the estuary, 16-21 days or 32 to 42 tidal cycles (Jeffries 1962), tends to retain pollutants entering the system and delay dilution with receiving waters. Over the last century the quality of the estuarine water has degraded in part due to eutrophication. Eutrophication disrupts the natural balance of the system, resulting in phytoplankton blooms of both increased frequency and intensity in response to over-enrichment. Noxious phytoplankton blooms are among the potential negative impacts, as are shifts to less desirable species of phytoplankton, diminished aesthetics (e.g., from brown tides) and changes in phytoplankton cell size. The latter can adversely effect the nutrition of organisms that have cell size-related food requirements (e.g. clams). Likewise, dense and accelerated phytoplankton blooms ultimately increase oxygen demand on the system leading to episodes of hypoxia.

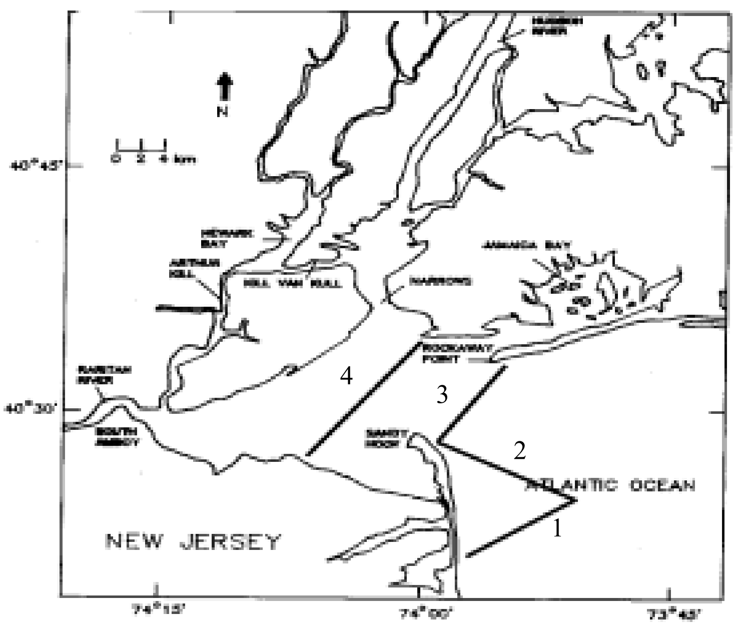

Fig.1. Map of the study site with the locations of the transects

2. Research Methods and Materials

Data acquisition for this study were composed of AVIRIS data over several transects covering the study site, simultaneous shipboard sampling and measurements of the underwater light field on July 11,1998. Sampling transects (1-4) as marked on figure 1 are located where the maximum taxonomic variability in phytoplankton community has been recorded, including the Narrows (transect 4), which receives fresh water from the Hudson River, and the Passaic and Hackensack Rivers. During times of low river flow, mostly treated sewage discharges contribute greatly to freshwater flow (Hires and Mellor, 1987). Transect 3, the Sandy Hook-Rockaway Transect is affected by the outflows of both the Hudson (north) and Raritan (south) systems. Transects 1 and 2 are just outside the estuary, off the New Jersey coast and within the area affected by the estuarine outflow. The sampling density included 4 locations along each of the predesignated transects. The grid system is compatible with airborne and satellite (SeaWIFS) spatial resolutions.

2. 1. Airborne visible/Infrared Imaging Spectrometer

The AVIRIS images the earth's surface in 224 spectral bands approximately 10 nm wide (nominal width is 9.6 nm) covering the region 400-2500 nm from a NASA ER-2 aircraft at an altitude of 20 km. The ground resolution is 20m * 20m. the instrument is composed of four spectrometers (A, B, C, and D). which record 32,64,64 and 64 bands each. Because of band overlap between the four spectrometers, there are 210 discrete bands available of which bands 1-73 are used in this study. AVIRIS records the integrated effects of the solar source, the atmosphere and the targeted surface. To compensate for the atmospheric effects in the AVIRIS data, an atmospheric and air-water interface correction algorithm based on MODTRAN 3 was utilized. All atmospheric calculations were performed in LOWTRAN mode.

2.2. Field Spectroradiometer

The Optronic OL 754 submersible spectroradiometer (which covers the spectral range from 300 nm to 850 nm) was used to obtain in situ field spectroradiometric measurements. The instrument functions at 1-10nm bandwidth (user selectable) allowing computation of normalized percentage reflectance curves. Subsurface downwelling/upwelling irradiance measurements was carried out by lowering the aperture into water. The instrument was linked to a shipboard computer where the spectroradiometric data were stored. These measurements are essential in modeling and calibration of remote sensing radiance measurements and their conversion to subsurface irradiance reflectance R(O-) for determination of optical water quality parameters. The subsurface irradiance reflectance can be derived from the remotely sensed upwelling radiation. This is the most appropriate parameters of underwater light field and it can be related to inherent optical properties of absorption and scattering (Petzolds, 1972 and Kirk, 1993). In short, the link between remotely sensed upwelling radiance and underwater inherent optical properties will be made through the spectroradiometric measurements.

2.3. Shipboard Sampling

Discrete shipboard samplings were collected along predesignated transects for chlorophyll pigment analysis. The sampling were obtained during the time period encompassing the aircraft overflight. The determination of chlorophyll-a and phaeopigment concentrations were based on methods described by Strickland and Parsons (1972) and Evans and O'Reilly (1987). Accordingly photosynthetic pigments from field samples were concentrated by filtering between 100 and 500 ml of water through Whatman GF/F filters and filters were fractionated through (20, 0.7, 0.2 μm) filters. Pigments were extracted in 10 ml 90% acetone in a darkened freezer for 24 hours. The plankton were present in moderate amounts in the samples. The dominant organism in the samples was identified as Rhizosolenia delecatula (diatom) with concentration of 1-2000 Rhizosolenia cells/ml. The non dominant species include flagellates and chlorophytes causing interferences. Due to the complexity of pigment composition in the field samples, Laboratory-based spectrophotometric techniques will be used for further verification.

3. Data Analysis and Model Development

3.1. The atmospheric correction

An atmospheric and air-water interface correction software called Toolkit which is based on MODTRAN 3 was utilized to correct AVIRIS data for atmosheric effects (De Haan et al, 1997). All atmospheric calculations were performed in LOWTRAN mode. From the AVIRIS scene of transect 1 a pixel was identified having the lowest reflectance at 500 nm. This spectrum was then used to determine an appropriate atmospheric composition which did not overcorrect or undercorrect this lowest reflectance spectrum. Several iterations led to the conclusion that, in lieu of accurate meteorological data, the following atmospheric circumstances led to a "reasonable" R(0-) spectrum (Table 1).

Table 1

parameter	parameterisation	source
Aerosol:	Maritime extinction	iterativeley selected
Atmosphere:	Midlatitude Summer	iterativeley selected
Horizontal visibility:	32 km	iterativeley determined
Sun zenith:	47.3°	calculated from AVIRIS UTC time
Sun azimuth:	96.6°	calculated from AVIRIS UTC time
View zenith:	180°	from AVIRIS header data
View azimuth:	60°	from AVIRIS header data
View altitude:	21 km	from AVIRIS header data

Subsequently these atmospheric parameters were applied to spectra from the Shrewsbury and the Navesink rivers. The results are shown in Fig 2. The graph shows that the atmospherically corrected spectra are noisy below approximately 450 nm and above 875 nm. Below 450 nm the noise may be due to a variety of causes (i.e., a wrong aerosol choice; a wrong atmosphere choice; a wrong horizontal visibility; Unsuitability of the LOWTRAN mode and relative insensitivity of AVIRIS) still have to be determined. Above 875 nm a likely candidate for the calculated (too) high R(0-) values is a poor estimation of the water vapor in the atmosphere.

3.2. Simulation of the R(0-) spectra using a bio-optical model for case II waters

An analytical bio-optical model was used to generate the subsurface irradiance reflectance, R(0-) from the constituent concentrations. Several models for ocean, coastal and inland waters were investigated by Gordon et. al..(1975), Morel and Prieur, (1977), Whitlock et. al.. (1981), Kirk, (1991), Dekker (1993) and Dekker et. al.. (1994). In this study the Gordon model is used adapted to Dutch inland lakes :

$$R = 0.31 \frac{b_b}{a + b_b} \qquad (1)$$

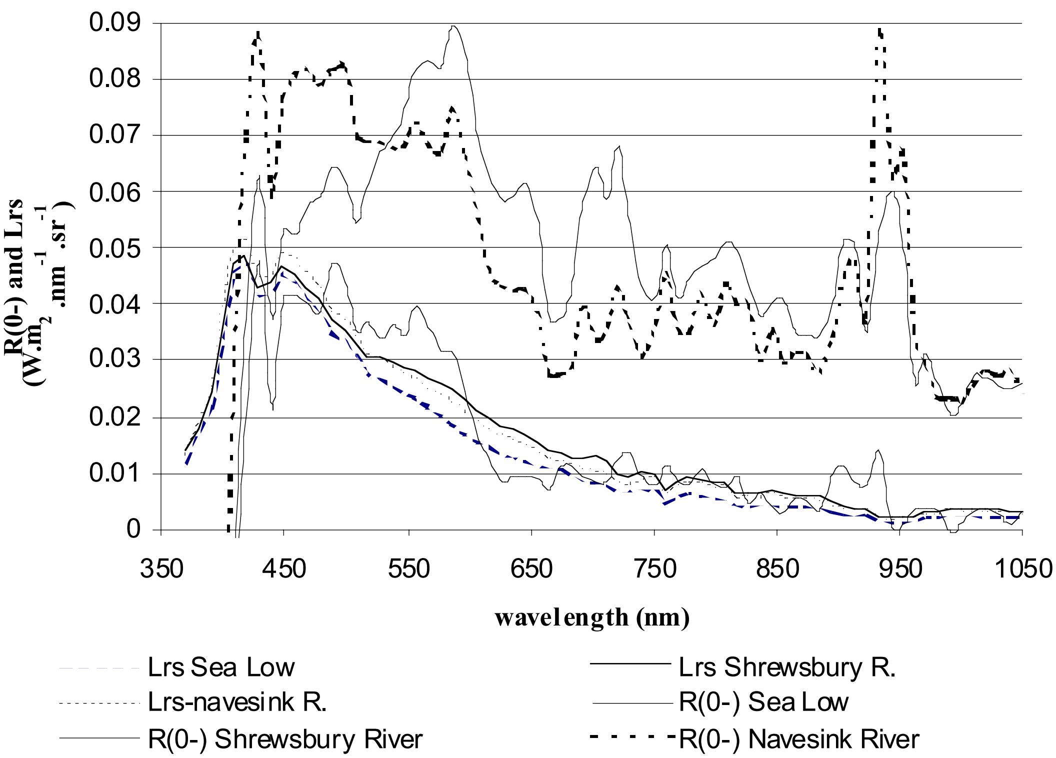

Fig. 2 AVIRIS Lrs spectra of selected locations and calculated R(0-) spectra for different water types

where a is the total absorption coefficient, b_b is the total backscatter coefficient and 0.31 is a factor that is dependent on geometry of the incoming light and the volume scattering in the water body. In this case the factor was calculated for 8 shallow eutrophic inland lakes in the Netherlands by fitting measured R(0-) spectra to measured inherent optical properties. The data may be found in Dekker (1993). The inherent optical properties a and b_b are assumed to be linear functions of the constituent concentrations. This allows the introduction of the specific inherent optical properties, i.e. the inherent optical properties per unit concentration : e.g. the specific inherent absorption by phytoplankton, a*ph, is the amount of absorption caused by 1 mg m-3 CHL. Utilizing Beer's law enables to write the total absorption coefficient a as a superposition of the absorption by phytoplankton, tripton (suspended particles excluding phytoplankton), gilvin and water. The concentrations of the constituents are given by CHL, DW and g440 (the absorption of gilvin at 440 nm)

$$a = a_{\mathrm{w}} + a^{*}_{\mathrm{dw}}\mathrm{DW} + a^{*}_{\mathrm{ph}}\mathrm{CHL} + a^{*}_{\mathrm{g}} g_{440} \tag{2}$$

$$b_b = b_{b\mathrm{w}} + b^{*}_{b\mathrm{dw}}\mathrm{DW}$$

The asterisks denote that a and b_b are specific inherent optical properties (SIOP), i.e. per unit concentration denoted by the subscript.

3.3. Spectral matching

As a first attempt at spectral matching we tried to match two extreme spectra measured from AVIRIS to simulations using the bio-optical model, by using input values of specific inherent optical properties as far as they were measured (i.e. dissolved organic matter absorption at 440 nm), and by validating using measured Secchi depth transparencies as a control. It was fairly easy to simulate the two R(0-) spectra from the sea and the Shrewsbury River using the bio-optical model. Table 2 gives the values that produced a good match and the spectra are presented in figure 3. The spectral matching was carried out perfunctionary (i.e. as soon as a reasonable coherence was found we stopped with further iteration). This was found to be more than sufficient, because a more rigorous approach is required to quantitatively perform this analysis.

Table 2

Chlorophyll (μg l-1)*	0	100
Tripton (mg l-1)*	1.5	25
DOM absorption at 440 nm (m-1)*	0.24	2
Secchi Depth transparency (m)**	4.02	0.33
* Iteratively determined values of concentrations ** calculated values		

During the sampling Secchi depth transparencies locally measured varied between 45 cm and 3 m. The value for DOM absorption at 440 nm in Shrewsbury River was iteratively adjusted to make the spectra fit at lower wavelengths.

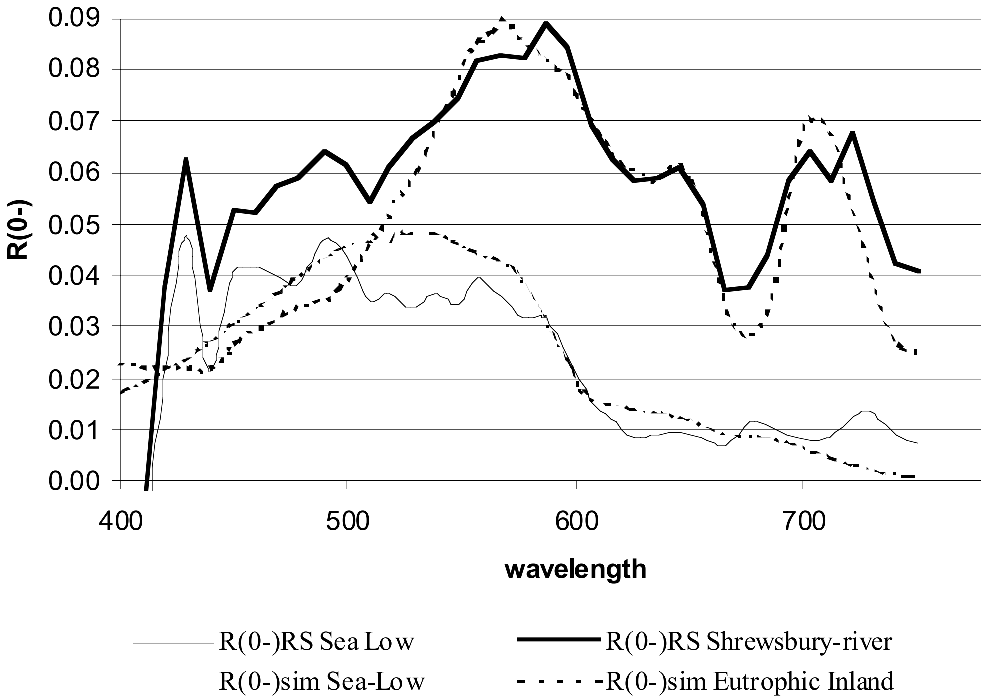

Fig.3. R(0-)spectra from atmospherically corrected AVIRIS and simulated data

Fig.3 shows that a reasonable fit could be obtained between calculated R(0-) spectra from the AVIRIS data and the bio-optical model simulated data in spite of a considerable amount of iteration and estimation of parameters. Ongoing research will look more closely into this dataset and perform a more rigorous analyses of the dataset. Nevertheless it is clear that it is feasible to use geophysical knowledge based models to derive solutions which are going to be a challenge to improve using a more thorough scientific methodological analysis. The preliminary results indicate that the approach of using specific inherent optical properties is a sound approach. It is highly probable that absorption and scattering cross-sections may have higher or lower values; thus allowing a significant variation in the above tabulated iteratively determined values. However, the shape of the cross-sections must be reasonably appropriate otherwise, it would be impossible to get such a close fit using the simple approach adopted here.

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